Chapter 1. Introduction

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1.1. Overview

The Fermilab Proton Source was constructed in the early 1970's and originally consisted of a proton ion source, a 750 kV Cockcroft-Walton, a 200-MeV Linac, and an 8 GeV Booster synchrotron. Since then the facility has undergone substantial improvements including the addition of a second Cockcroft-Walton, conversion to H^- ions for acceleration through the Linac and charge-exchange injection into the Booster, and a Linac energy upgrade to 400 MeV. However the Booster itself is basically the same machine that was built three decades ago. This facility currently provides proton beams at intensities up to 5×10^{12} protons per pulse (6×10^{10} protons/bunch $\times$ 84 bunches), at 8.9 GeV/c, for injection into the Main Injector in support of Tevatron Collider and Main Injector fixed target operations. Most Proton Source hardware is capable of 15 Hz operation without beam and a few Hz with beam.

With the advent of the Main Injector, the demand for protons in support of a diverse physics research program at Fermilab is growing. The reason is that the Main Injector creates a new capability for simultaneous operation of the collider and 120 GeV fixed target programs. In parallel the utility of the Booster itself as a source of protons for fixed target neutrino experiments has also been identified. Two experiments are now under construction, the Neutrinos at the Main Injector (NUMI) project and the MiniBooNe (Booster Neutrinos), that utilize protons delivered from the Booster either via the Main Injector or directly. These experiments require not only the full 5×10^{12} protons per pulse intensity of the proton source (or more), but a 7.5 Hz repetition rate. Two experiments under consideration at the current time, Kaons at the Main Injector (KAMI) and Charged Kaons at the Main Injector (CKM), could also place demands on the proton source over the coming decade. Finally, a number of future initiatives are in various states of consideration — the BTeV experiment has stage 1 approval as a continuation of the Fermilab collider program, a neutrino source based on a muon storage ring (aka "neutrino factory") and a Very Large Hadron Collider have been identified as possible long range facilities for Fermilab. Low energy antiproton facilities also are receiving attention. Each of the near term activities would benefit from an improvement in the per pulse and per hour intensities delivered from the existing Proton Source, while the longer term possibilities would demand performance beyond the capabilities of the existing proton source, even with substantial additional improvements.

The purpose of this study is to outline a possible design of a new Proton Source that could satisfy the demands of the future Fermilab research program for the next several decades. The goal is to outline a staged plan, with significant enhancements to the Fermilab research program evident at each step, with minimal disruption to the ongoing program from required construction activities, and with maximal flexibility in meeting future demands. As will be described in this document, we believe that such a plan would consist of some or all of the following components:

- Replacement of the Booster by a modern synchrotron of considerably greater capabilities
- Upgrading of the Linac energy and intensity
- Addition of a second synchrotron to further augment the long-term capabilities

An evolutionary implementation of these improvements is envisaged, with benefits accruing to the Fermilab program at each stage. The timing of these stages as well as the possible consolidation of multiple stages will presumably be dictated by the occurrence of normally scheduled program interruptions, by the availability of funding, and by the future direction of the Fermilab research program. Mostly for historical reasons, two phases of this plan have been identified, and furthermore, Phase I has two stages. Primary design criteria have been established, in chronological order, as follows:

Near term (Phase I, Stage 1)

- Replacement of the Booster by a synchrotron capable of delivering 2.4×10^{11} protons/bunch (4 $\times$ current performance) with beam delivered at a rate of 15 Hz and with a kinetic energy of at least 8 GeV and at most 16 GeV.
- Compatibility with injection of this increased bunch intensity into the Main Injector utilizing the existing 53 MHz Main Injector rf system.

Neutrino Factory era (Phase I, Stage 2)

- A capability for delivering 1 MW of protons onto a production target with a 7.5 MHz bunch structure, while maintaining compatibility with Main Injector injection.

Longer term (Phase II, Muon Collider Era)

- A capability of delivering 4 MW of protons onto a production target with a bunch structure matched to the needs of a muon collider.

This document describes a particular scenario based on the above considerations, a plan that includes a 16 GeV Booster replacement, a 1 GeV Linac upgrade, and a 3 GeV Pre-Booster. This scenario is regarded as representative but not necessarily optimal. The design described in the body of this report primarily addresses Phase I, the items listed through the “Neutrino Factory Era”. The report also includes a preliminary assessment of the costs associated with that design. The cost and performance implications of choosing a different operating energy are discussed in Appendix B. Discussion of the modifications required to support the “Phase II, Muon Collider Era” are included in Appendix C. Impacts on the Fermilab program of each step are discussed, as are technical issues and areas of fruitful R&D.

1.2. Present Performance of the Proton Source

The performance of the Proton Source can be characterized by the number of protons per bunch, the number of protons per second, and the transverse and longitudinal emittances of the beam. Under current operating conditions the number of protons per bunch is fundamentally limited by the space charge tune shift achievable at the 400 MeV injection energy and the aperture of the machine, the number of protons per second by the losses during injection, acceleration, and extraction coupled with the available shielding, the transverse emittance by the space charge forces at injection, and the longitudinal emittance by the momentum spread delivered from the Linac and our ability to control longitudinal instabilities. Figures 1.1 and 1.2 characterize current performance.

Figure 1.1 displays Booster performance, as measured by transverse beam emittance (95%, normalized), as a function of intensity. Two sets of points are included: the "200 MeV" points refer to pre-September 1993 operations when the injection energy was 200 MeV. The "400 MeV" points refer to current operations with a 400 MeV injection energy. It has long been believed that Booster performance is limited by space charge forces at injection. The straight lines through the points represent contours of constant space-charge tune shift (~0.4) as calculated at the injection energy. The data demonstrate that the improved performance attained by raising the injection energy is as anticipated based on a fixed space-charge tune shift limit. By way of reference, the Booster and Main Injector apertures are approximately 20 π and 40 π mm-mrad respectively. As can be seen from the figure, an emittance of 15 π mm-mrad from the Booster is characteristic of the nominal Main Injector operating intensity of 6×10^{10} protons/bunch.

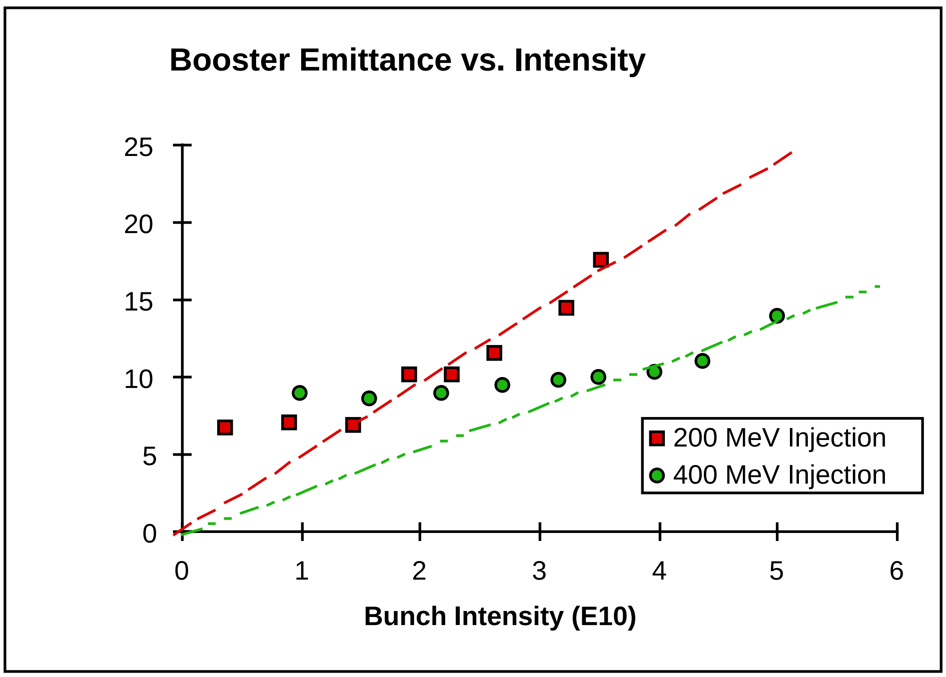

Figure 1.1 Measured transverse beam emittance (95%, normalized, in π mm-mrad) delivered from the 8 GeV Booster as a function of beam intensity

Figure 1.2 shows the performance of the Booster as measured in longitudinal emittance (95%, per bunch) during the period covered by operations with 200 MeV and 400 MeV injection energies. Based on extrapolation of the 200 MeV points, the Main Injector was designed with an acceptance of 0.6 eV-s. As can be seen, the achieved performance is dramatically better than had been assumed. This improvement comes not only from increasing the injection energy but also from the implementation of dampers to control several longitudinal coupled bunch modes. The improved performance has created options for increased Main Injector intensities based on slip stacking, a subject that is beyond the scope of this report.

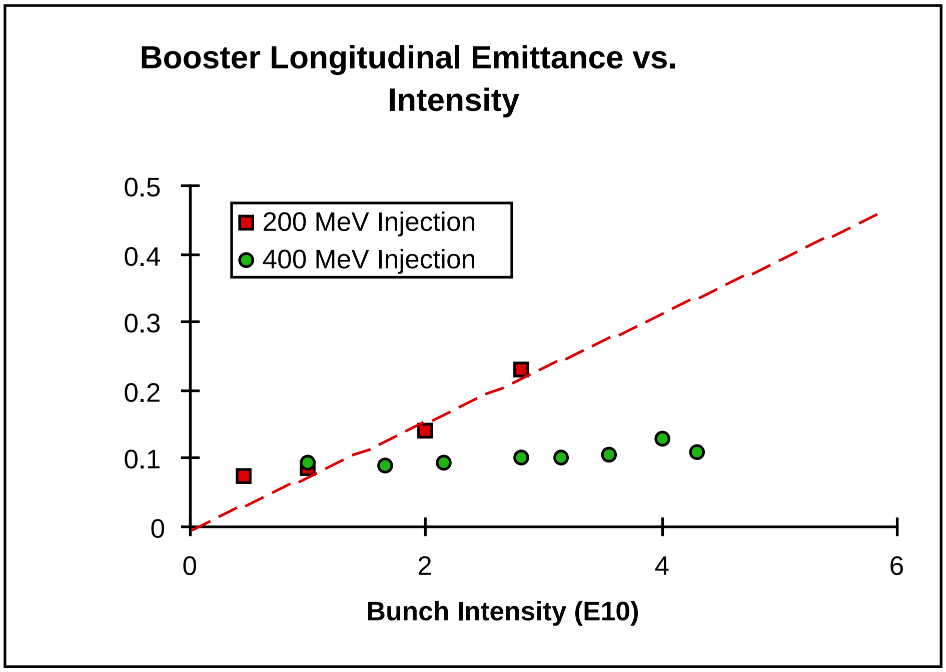

Figure 1.2 Measured longitudinal beam emittance (95%, in eV-s) delivered from the 8 GeV Booster as a function of beam intensity

The above data suggest that the Booster can produce beam pulses having intensity and emittances corresponding to Main Injector design specifications. However, beam losses in the Booster are a major problem. Passive radiation shielding of the Booster is inadequate even for present operations, and options for additional shielding in the current configuration are extremely limited. The maximum proton delivery rate is limited by the ability to fine-tune beam losses within a safety envelope enforced by an array of some fifty interlocked radiation detectors. Since the Booster was originally designed, the implications of beam-on radiation external to the enclosure have been exacerbated by the increased demand for protons, by construction of office and laboratory space in the immediate vicinity of the machine, by relocation of the extraction point to an area below an office building, and by tighter regulations on allowable radiation doses. Extrapolation of the present readings of those detectors to the intensities required by approved near-future programs (MiniBooNe and NUMI) shows that several of these interlocked detectors would exceed their allowed values by factors as large as 20.

Independent of shielding issues, maintenance of beamline components will become a significant operational problem due to component activation. Given present machine performance, activation levels may rise two orders of magnitude from present levels based on the proton demands for approved experiments. For example, current dose rates of 20-50 mRem/hr at one foot from rf cavities will rise to 2000-5000 mRem/hr.

The current performance of the Proton Source (6×10^{10} protons/bunch with a transverse emittance of 15 π mm-mrad and a longitudinal emittance of 0.1 eV-s/bunch) is sufficient to support the goals of antiproton production for Run II, NUMI or KAMI, and the fast extracted neutrino experiment MiniBooNE — assuming the implementation of effective solutions to the beam loss problems in the Booster that will allow operations beyond 1.2×10^{16} protons per hour. Utilization of the Proton Source in support of a neutrino factory and/or a muon collider are both clearly beyond current capabilities. Support for an upgrade of the Tevatron Collider may or may not be within current capability, depending on the antiproton production strategy implemented.

1.3. Design Criteria for the Proton Driver

Support for muon facilities is by far the biggest challenge for a future Proton Source at Fermilab. The requirements for a neutrino factory based on a muon storage ring include the capability of providing, at a reference energy of 16 GeV, 3×10^{13} protons per pulse (4.5×10^{14} protons per second, 1.6×10^{18} protons per hour). In addition, the shielding requirements associated with delivering 1.6×10^{18} protons per hour are so far beyond the capabilities of the present Booster that a relocation of the Proton Source is unavoidable. These specifications correspond to a beam power of 1.2 MW. A muon collider would be even more demanding, requiring 10^{14} protons per cycle or about 4 MW of beam power.

Design criteria have been established for an upgraded Proton Source based on the requirements of the near term program and a program including support for a neutrino factory, with an auxiliary goal of defining a configuration that simultaneously enhances Fermilab's ability to support the broad scope of hadron-based capabilities described above. The design criteria so derived form the basis for choosing the major machine parameters shown in Table 2.1.

1.4. Why do we need a new Booster?

Upon hearing that we were working on the design of the Proton Driver, some of our colleagues asked “Why do we need a new Booster?” or “Why not upgrade the Booster instead of replacing it?” or some other variant of that question. Although the answers to those questions are contained implicitly in this report, it is perhaps appropriate at this point to address them explicitly because the answers will serve as a preview of the contents of this document.

For clarity in communicating with those colleagues, it was useful first to turn the question around by asking “What major Booster subsystem(s) do you think ought to be reused?” They answered that question in various ways. To give an extreme example, at least one person thought that the Booster tunnel was the only subsystem worth reusing, while at least one other colleague thought that it was the only subsystem that ought to be replaced. It is appropriate to examine individually the major cost drivers: the tunnel, the magnets, and the rf systems.

1.4.1. Reuse the Booster tunnel?

The decision not to reuse the Booster tunnel was based on the following factors:

- Shielding problems: The existing tunnel is not deep enough to provide passive shielding against radiation problems at the surface. The losses from the present Booster are already problematical; approved near-future programs already require an "electronic berm" that may cause frequent trips unless the basic beam-loss problems are greatly alleviated. The new Proton Driver is designed to accelerate much more beam power.

- Size and shape constraints: The size and shape of the existing tunnel would have severely constrained the accelerator lattice design. The existing tunnel is a 24-sided regular polygon, almost a perfect circle. That would limit the length of straight sections and the locations of dipoles, so it would have been difficult if not impossible to design a modern lattice with space for rf cavities in dispersion-free straight sections, transition avoidance, and room for a 1 GeV H^- injection system. Of course the circumference of the new machine would have had to be very close to that of the Booster, which may or may not be optimal. The 16-GeV machine described in this report has a circumference 1.5 times that of the Booster and obviously would not fit in the existing tunnel.

- Location constraints: There is no obvious place to put a Linac energy upgrade or a Pre-Booster near the existing Booster tunnel. A new tunnel can be located optimally so as to allow space nearby on the site for the other possible new devices.

- Relative costs of civil construction: The question about reusing the Booster tunnel is of course motivated by the desire to save money, and reusing it would indeed save the cost of constructing a new tunnel. However, that saving must be weighed against the direct and indirect costs of reusing the existing tunnel. The advice from Fermilab civil construction experts was that the cost of adapting and retrofitting the Booster tunnel and galleries for the Proton Driver would be comparable to that of a new tunnel. For example, the galleries would require extensive shielding augmentations to make them usable, and then would have to be substantially enlarged to house Proton Driver components such as the massive capacitors and chokes of the 15-Hz resonant circuits. The demolition and replacement costs of buildings rendered unusable, such as the Booster towers, would also be considerable.

- HEP Downtime: Phase I would require a longer interruption in the high-energy physics program if the Booster were replaced with another machine in the same tunnel.

1.4.2. Reuse the Booster guide field magnets?

The decision not to reuse the Booster guide field magnets was based on the following factors:

- Lattice design limitations: The Booster guide field magnets are combined-function or gradient magnets. For the existing lattice the transition energy is in the middle of the operating range. It is unlikely that any new arrangement of the magnets would circumvent that problem, because in order to move transition out of the operating range the lattice designers need independent control over the location of dipole and quadrupole fields. The achievement of other desirable features of the lattice such as dispersionless straight sections and control of betatron tunes is also constrained by having only gradient magnets to work with.

- Aperture: The physical aperture of the Booster gradient magnets is about half the linear dimension needed for the baseline Proton Driver in each plane. Worse yet, field quality problems limit the dynamic aperture to a value considerably smaller than the physical aperture.

- Strength: The peak field of the gradient magnet is only about 0.8 T. The magnets have been operated at fields corresponding to a kinetic energy as high as 10 GeV, a value limited by the saturation of the backlegs.

- Beam impedance issues: The magnets have no beam pipe and no liner to carry the beam image currents. The resulting high impedances make the beam susceptible to instabilities.

1.4.3. Reuse the Booster rf cavities?

In connection with the Proton Driver design effort, there is a research and development program, detailed in this report, to upgrade the existing Booster rf cavities. The major goals are higher accelerating voltage and a larger physical aperture. Considerable mechanical renovation of these 30-year-old systems is also necessary. Besides being useful for the existing Booster, the upgraded cavities would be used in the Proton Driver for Stage 1 of Phase I. Of course, new cavities would still be needed to produce the 7.5 MHz bunch spacing required in Stage 2.